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SHIELDING STAGNATION SURFACES OF FINITE CATALYTIC ACTIVITY BY AIR INJECTION IN HYPERSONIC FLIGHT

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SHIELDING STAGNATION SURFACES OF FINITE CATALYTIC ACTIVITY BY AIR INJECTION IN HYPERSONIC FLIGHT

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SUMMARY

A study was made on the effect of air injection in shielding stagnation surfaces, which have various finite catalytic activities, from the aerodynamic heating in hypersonic flight. Only the case of chemically frozen boundary layer was considered.

A set of closed-form solutions was obtained which enables one to calculate heat-transfer rate when the blowing rate and the catalytic characteristics of the surface material are given.

It was found that air injection can strongly influence the heat acceptance rate of a catalytic surface and can thus be used to control the heat input to surfaces on which catalytic activity varies widely with temperature and flight condition.

Only small amounts of air are required for large reductions in heat-transfer rate.

INTRODUCTION

In a hypersonic flight it has been shown (refs. 1 and 2) that the diffusion of the radicals through the boundary layer and the subsequent homogeneous or heterogeneous recombination could increase the heat transfer to the surface by a magnitude which is comparable to that due to the ordinary convection. It is estimated in reference 2 that, for a rather large domain of flight conditions, at the stagnation point the chemical reaction time is large compared to the characteristic times for flow and radical diffusion. For such a frozen flow, cooling of the surface by the injection of a fluid seems attractive because an effective cooling may be accomplished if the surface is shielded from the hot gas and also from the incoming radicals.

A general qualitative analysis of the heat transfer with mass addition for a chemically frozen flow in the boundary layer was included in reference 3. It is possible from the information given in the reference to calculate the heat transfer to an infinitely catalytic surface.

A catalytic reaction, however, usually takes place at a finite rate. In reference 2, a closed-form solution to the problem of stagnation region heat transfer was obtained for the frozen boundary layer and for the surfaces with different finite catalytic activities. The approximation shown in reference 4 for a highly cooled stagnation surface was incorporated in the analysis of reference 2 in order to obtain a closed-form solution.

In the present paper, essentially the same approach found in reference 2 will be used to study the usefulness of air injection in shielding surfaces with different finite catalytic efficiencies from heat transfer.

SYMBOLS

C	$\frac{\rho\mu}{\rho_e\mu_e}$
c_{pi}	specific heat of ith component, Btu/lb °F
$\overline{c_p}$	frozen specific heat of the mixture, $\Sigma_i m_i c_{pi}$, Btu/lb °F
d	nose diameter, ft
D	binary diffusion coefficient, ft^2/sec
f,F	dimensionless stream functions
f_w	dimensionless blowing rate, $-\frac{\rho_w v_w}{\sqrt{2\beta(\rho_e\mu_e)_s C}}$
g	$\frac{h(\eta)}{h_e}$
h	frozen total enthalpy, Btu/lb
h_t	total enthalpy, $h + m\Delta h^o$, Btu/lb
Δh^o	heat of recombination of atoms, Btu/lb
k	thermal conductivity, Btu/sec ft °F
K_w	catalytic reaction rate constant, ft/sec
Le	Lewis number, $\frac{Pr}{Sc}$
m	mass fraction of atoms
m_i	mass fraction of ith component

p	pressure, lb/sq ft
Pr	Prandtl number, $\frac{\mu \bar{c}_p}{k}$
q_c	heat transfer to the surface by ordinary convection, Btu/sec sq ft
q_d	heat transfer to the surface by atom recombination at the surface, Btu/sec sq ft
q_t	total heat transfer to the surface, $q_c + q_d$, Btu/sec sq ft
q_{t_o}	total heat transfer to noncatalytic and nonporous surface, Btu/sec sq ft
q^*	dimensionless heat transfer, $\frac{q_t}{h_{te}\sqrt{\beta(\rho_e \mu_e)_s C}}$
r_o	distance defined in figure 1
s	similarity abscissa
Sc	Schmidt number, $\frac{\mu}{\rho D}$
T	temperature, $^{\circ}$R
u	x component of velocity, ft/sec
v	y component of velocity, ft/sec
x	abscissa, ft
y	ordinate, ft
Z	$\frac{m(\eta)}{m_e}$
β	$\frac{du_e}{dx}$
η, ξ	similarity ordinates
μ	viscosity, lb-sec/ft^2
ρ	density, lb/ft^3
φ	catalytic influence factor defined by equation (22)
ψ	stream function

Subscripts

e outer edge of the boundary layer

s stagnation point

w surface condition

∞ free-stream condition

Superscript

' total differentiation with respect to the variable concerned

ANALYSIS

Boundary-Layer Equations and Boundary Conditions

For a frozen laminar boundary layer on axisymmetric bodies, one may begin with the following usual set of equations (see fig. 1 for coordinate systems).

$$\frac{\partial(\rho u r_o)}{\partial x} + \frac{\partial(\rho v r_o)}{\partial y} = 0 \qquad \text{(continuity)} \qquad (1)$$

$$\rho u\left(\frac{\partial u}{\partial x}\right) + \rho v\left(\frac{\partial u}{\partial y}\right) = \frac{\partial}{\partial y}\left(\mu\,\frac{\partial u}{\partial y}\right) - \frac{dp}{dx} \qquad \text{(momentum)} \qquad (2)$$

$$\rho u\left(\frac{\partial h}{\partial x}\right) + \rho v\left(\frac{\partial h}{\partial y}\right) = \frac{\partial}{\partial y}\left(\frac{k}{c_p}\,\frac{\partial h}{\partial y}\right) - \frac{\partial}{\partial y}\left[\mu\left(\frac{1}{Pr} - 1\right)\frac{\partial(u^2/2)}{\partial y}\right] \qquad \text{(energy)} \qquad (3)$$

$$\rho u\left(\frac{\partial m}{\partial x}\right) + \rho v\left(\frac{\partial m}{\partial y}\right) = \frac{\partial}{\partial y}\left(\rho D\,\frac{\partial m}{\partial y}\right) \qquad \text{(diffusion)} \qquad (4)$$

The radiation term is neglected in the derivation of the energy equation. It is possible to obtain similarity solutions to the above equations provided the boundary conditions do not destroy the similarity. In reference 2, a set of boundary conditions was derived which preserved similarity for the case of no fluid injection at the stagnation region. That the similarity is not destroyed even when the fluid injection is added will be shown subsequently. With this in mind the usual similarity transformation is applied as follows:

Let

$$\rho u r_o = \frac{\partial\psi}{\partial y}$$

$$\rho v r_o = -\frac{\partial\psi}{\partial x}$$

$$s = \int_0^x \rho_e \mu_e u_e r_o^2 dx$$

$$\eta = \frac{u_e r_o}{\sqrt{2sC}} \int_0^y \rho \; dy$$

$$\frac{u}{u_e} = f'(\eta)$$

then

$$f(\eta) = \frac{\psi}{\sqrt{2sC}}$$

where C is assumed to be constant in the transformation. Also define

$$g(\eta) = \frac{h(\eta)}{h_e} \quad \text{and} \quad Z(\eta) = \frac{m(\eta)}{m_e}$$

Then the continuity equation is automatically satisfied and equations (2) through (4) transform to

$$f''' + ff'' = \frac{2s}{u_e}\left(\frac{du_e}{ds}\right)\left(f'^2 - \frac{\rho_e}{\rho}\right) \tag{5}$$

$$fg' + \frac{1}{Pr} g'' = \frac{u_e^2}{h_e}\left(\frac{1}{Pr} - 1\right)(f'f'')' \tag{6}$$

$$fZ' + \frac{1}{Sc} Z'' = 0 \tag{7}$$

It was shown in reference 4 that the terms in the right-hand side of equations (5) and (6) can be neglected without causing any appreciable error in the solutions when the stagnation region is highly cooled. This original argument of reference 4 was for the case of no fluid injection only. The same argument, however, holds also when a fluid is injected at the surface, and this case was discussed in reference 5. When this simplification is made, the equations (5), (6), and (7) can be written as:

$$f''' + ff'' = 0 \tag{8}$$

$$fg' + \frac{1}{Pr} g'' = 0 \tag{9}$$

$$fZ' + \frac{1}{Sc} Z'' = 0 \tag{10}$$

The boundary conditions are

$$f(0) = f_w$$

$$f'(0) = 0$$

$$f'(\infty) = 1$$

$$g(0) \ll 1$$

$$g(\infty) = 1$$

$$Z(\infty) = 1$$

A catalytic reaction rate can be usually expressed by the following relation.

$$\text{Reaction rate} = K_w(\rho_w m_w)^n$$

where K_w is a specific rate constant for the catalytic reaction, and the exponent n represents the order of the reaction. In general, the catalytic surface recombination of the dissociated gases such as oxygen and nitrogen can be considered as a first-order reaction (see ref. 2). The mass balance of atoms at the surface yields the following boundary condition for $n = 1$

$$\rho_w D_w \left(\frac{\partial m}{\partial y}\right)_w - \rho_w v_w m_w = K_w \rho_w m_w \tag{11}$$

The left-hand side of the above equation represents the net rate of atoms arriving at the surface whereas the right-hand side represents the net rate of disappearance of the atoms by the catalytic recombination at the surface. The following relations are used throughout this report.

$$r_o(x) = x \ , \qquad \rho_e\mu_e = (\rho_e\mu_e)_s \ , \qquad u_e = \beta x \tag{12}$$

Now the boundary condition (eq. (11)) is transformed to the dimensionless form as

$$Z'(0) = Sc\left[\frac{K_w \rho_w}{\sqrt{2\beta(\rho_e \mu_e)_s C}} - f_w\right] Z(0) \tag{13}$$

It is seen that the boundary condition (13) does not destroy the similarity of the solution.

Solution of the Equations

Tabulated values of the Blasius function with blowing are available elsewhere (refs. 6 and 7). These tabulations, however, are for the boundary condition of $f'(\infty) = 2$. These can be made to fit the present case $f'(\infty) = 1$ readily. Denote the Blasius function tabulated in the references 6 and 7 by $F(\xi)$, and the present function of equation (8) by $f(\eta)$. Then $F'(\infty) = 2$ whereas $f'(\infty) = 1$.

Let

$$F(\xi) = \sqrt{2}\ f(\eta) \tag{14}$$

and

$$\eta = \sqrt{2}\ \xi$$

Then the set found in the references

$$F'''(\xi) + F(\xi)F''(\xi) = 0$$

$$F'(0) = 0 \qquad F'(\infty) = 2 \qquad F(0) = F_w$$

becomes equation (8) with its boundary conditions

$$\left.\begin{aligned} f'''(\eta) + f(\eta)f''(\eta) &= 0 \\ f'(0) = 0 \qquad f'(\infty) = 1 \qquad f(0) &= f_w = \frac{1}{\sqrt{2}} F_w \end{aligned}\right\} \tag{15}$$

Therefore the tabulated values found in the references can be used here provided one remembers the changes in the values of one of the boundary conditions: $f_w = (1/\sqrt{2})F_w$. The set

$$\left.\begin{aligned} F(\xi)S'(\xi) + \frac{1}{Pr} S''(\xi) &= 0 \\ S(0) = 1 \qquad S(\infty) &= 0 \end{aligned}\right\} \tag{16}$$

was solved in reference 6 for $Pr = 0.72$ and $F_w = 0$, -0.5, -0.75, and and -1.0. Let

$$g(\eta) = 1 - S(\xi)$$

Then equation (16) becomes

$$\left.\begin{aligned} f(\eta)g'(\eta) + \frac{1}{Pr}\, g''(\eta) = 0 \\ g(0) = 0 \qquad g(\infty) = 1 \end{aligned}\right\} \tag{17}$$

which is the equation (9) with its proper boundary conditions. Integration of the diffusion equation (10) with the boundary condition $Z(\infty) = 1$ gives

$$1 - Z(0) = \frac{\sqrt{2}\ Z'(0)}{[F''(0)]^{Sc}} \int_0^\infty [F''(\xi)]^{Sc} d\xi \tag{18}$$

The application of the boundary condition of equation (13) to the above equation gives

$$Z(0) = \frac{1}{1 + \left\{\sqrt{2}\ Sc/[F''(0)]^{Sc}\right\}\left\{[K_w\rho_w/\sqrt{2\beta(\rho_e\mu_e)_s C}] - f_w\right\} \int_0^\infty [F''(\xi)]^{Sc} d\xi} \tag{19}$$

Heat-Transfer Rate at Surface

By utilizing the solution of (16), the heat transfer to the surface by ordinary convection becomes:

$$q_c = -\frac{S'(0)}{Pr}\, h_e\sqrt{\beta(\rho_e\mu_e)_s C} \tag{20}$$

The value $S'(0)$ is obtained directly from reference 6 for the four injection rates of $F_w = 0, -0.5, -0.75$, and -1.0. Next, the heat transfer to the surface due to the atom recombination at the surface is

$$q_d = \Delta h^o m_w K_w \rho_w = \Delta h^o m_e Z(0) K_w \rho_w$$

When the expression for $Z(0)$ given in equation (19) is used this becomes

$$q_d = \frac{m_e \Delta h^o \sqrt{\beta(\rho_e\mu_e)_s C}}{G}\, \varphi \tag{21}$$

where

$$\varphi = \frac{1}{1 + [\sqrt{\beta(\rho_e\mu_e)_s C}/G K_w \rho_w](1 - \sqrt{2}\ G f_w)} \tag{22}$$

and

$$G = \frac{Sc}{[F''(0)]^{Sc}} \int_0^\infty [F''(\xi)]^{Sc} d\xi \tag{23}$$

The catalytic influence factor φ of equation (22) becomes identical to that given in reference 2 when $f_w = 0$.

It is seen, from references 1 through 4, that the Prandtl number of 0.72 and the Lewis number of 1.4 are good approximations for the hypersonic boundary layer. In the numerical work, therefore, the Schmidt number is considered to be 0.72/1.4 = 0.514.

This author was unable to find elsewhere the values of the integral $\int_0^\infty [F''(\xi)]^{0.514} d\xi$. It is, therefore, calculated here by Simpson's rule for the three injection rates used for q_c, and it is tabulated here as follows:

$-F(0)$	$\int_0^\infty [F''(\xi)]^{0.514} d\xi$
0.50	2.472
.75	2.651
1.00	2.874

Finally, the expressions for total heat transfer ($q_t = q_c + q_d$) are derived from the equations (20) and (21) for the three injection rates and are found to be as follows. Total heat transfer for the case of no injection is taken from reference 2 and shown here for completeness.
For $f_w = 0$

$$q_t = 0.827 \sqrt{\beta(\rho_e \mu_e)_s C}\, h_{te}\left[1 + \frac{m_e \Delta h^o}{h_{te}} (1.251\,\varphi - 1)\right] \tag{24}$$

where

$$\varphi = \frac{1}{1 + 1.033[\sqrt{\beta(\rho_e \mu_e)_s C}/K_w \rho_w]}$$

For $f_w = -0.354$

$$q_t = 0.462\sqrt{\beta(\rho_e\mu_e)_s C}\; h_{te}\left[1 + \frac{m_e\Delta h^o}{h_{te}}(1.375\,\varphi - 1)\right] \tag{25}$$

where

$$\varphi = \frac{1}{1 + 1.135[\sqrt{\beta(\rho_e\mu_e)_s C}/K_w\rho_w]}$$

For $f_w = -0.530$

$$q_t = 0.295\sqrt{\beta(\rho_e\mu_e)_s C}\; h_{te}\left[1 + \frac{m_e\Delta h^o}{h_{te}}(1.499\,\varphi - 1)\right] \tag{26}$$

where

$$\varphi = \frac{1}{1 + 1.193[\sqrt{\beta(\rho_e\mu_e)_s C}/K_w\rho_w]}$$

For $f_w = -0.707$

$$q_t = 0.140\sqrt{\beta(\rho_e\mu_e)_s C}\; h_{te}\left[1 + \frac{m_e\Delta h^o}{h_{te}}(1.769\,\varphi - 1)\right] \tag{27}$$

where

$$\varphi = \frac{1}{1 + 1.248[\sqrt{\beta(\rho_e\mu_e)_s C}/K_w\rho_w]}$$

The above equations are for $Pr = 0.72$ and $Le = 1.4$. The general mode of the dependence of heat transfer on the property $(\rho\mu)$ was found in reference 1 for boundary layers of air molecule-atom mixture. It was suggested in reference 3, on the basis of the information given in reference 1, to use the value of $C = (\rho_w\mu_w/\rho_e\mu_e)^{0.2}$ in calculating heat transfer through such boundary layers. The use of this value of C, therefore, in the final equations (24) through (27) probably would yield best results in the calculation of the heat transfer.

RESULTS AND DISCUSSION

It can be estimated, from the information given in reference 2, that the boundary layer will be frozen at the stagnation region for the flight range between 200,000 feet altitude, 10,000 feet per second velocity, and 250,000 feet altitude, 25,000 feet per second velocity. The flight parameters $\sqrt{\beta(\rho_e\mu_e)_s C}$ and $m_e \Delta h^o/h_{te}$ vary approximately between 1 to 15×10^{-3} lb/sec-ft^2 and 0.3 to 0.7, respectively, in this range. These are for nose diameters between about 30 to 300 inches. The property values used here are obtained from references 8 and 9.

The effect of variation of $\rho_w K_w$ on the catalytic influence factor φ is shown in figure 2. The flight condition $\sqrt{\beta(\rho_e\mu_e)_s C}$ and the dimensionless injection rate f_w are used as parameters. The catalytic reaction rate constant K_w is a property of a particular combination of the reacting gas and the catalytic surface, whereas ρ_w is the density of the gas at the surface. Metallic and metallic oxide surfaces have much higher rate constants than nonmetallic surfaces for a given gas reaction. For instance, at the surface temperature of 700° K, the magnitude of K_w for oxygen recombination is in the order of 10^{-2} ft/sec for glasses whereas it is in the order of 10 ft/sec for metallic surfaces. The product $\rho_w K_w$ usually increases with temperature up to 1300° K or higher. According to the limited information available, it increases with $\sqrt{T_w}$ for glasses, but for some metals K_w increases with as much as $(T_w)^7$. These values are estimated from the information given in references 2 and 10.

It is seen from figure 2 and the brief analysis on K_w given above that the catalytic influence factor φ may vary readily between 0 and 1. It is also seen that the variation depends greatly on the surface material, surface temperature, and the flight parameter $\sqrt{\beta(\rho_e\mu_e)_s C}$ but it is rather insensitive to the injection rate f_w.

The variation of heat transfer with respect to the injection rate is shown in figure 3 in a dimensionless form. The three plots of the figure are for the three different ratios of heat-transfer potentials $\Delta h^o m_e/h_{te}$. The ratio $\Delta h^o m_e/h_{te}$ represents the fraction of the total heat-transfer potential available as recombination energy. In each of the plots, the catalytic influence factor φ is used as a parameter because it has been found that φ is not varied much with f_w when other factors remain constant. A large decrease in the heat transfer due to fluid injection is evident from the figure.

It is seen in figure 3 that the rate of decrease of heat transfer with increasing injection rate is greater for larger values of φ. This means that for a given rate of fluid injection, the amount of decrease in heat transfer from the case of no injection becomes greater with increasing φ. This is more evident for the higher values of $\Delta h^o m_e/h_{te}$ because the surface shielding from the incoming radicals by fluid injection becomes more prominent for higher potentials of recombination energy.

The considerable instability which may occur in hypersonic flight as a result of the increase in φ and the accompanying increase in heat transfer is discussed in reference 10. Under such conditions, one may see from the preceding discussions of the figure 3 that a well-programed injection rate would reduce the instability successfully.

The weight of a coolant carried is an important factor to be considered in an actual flight of a vehicle. The values of β, which appear in equation (12), must be known in order to have a specific numerical example. The symbol β represents the gradient du_e/dx and is obtained from the inviscid flow conditions of air at the outer edge of the boundary layer. It depends on several parameters, one of which is the nose shape. Many references can be found in the literature which describe the inviscid aerodynamics near the nose of a blunt body in hypersonic flight. Here, for the purpose of a numerical example, it is considered that the inviscid flow field is approximated by that near the stagnation point of a finite sphere. For such a region, β was found to be $(2u_\infty/d)\sqrt{(\rho_\infty/\rho_{es})[2-(\rho_\infty/\rho_{es})]}$ in reference 11, and this expression is used in the present calculation. The variation of heat transfer to the surface with respect to the actual injection rate of air in lb/sq ft-sec is shown in figure 4 for a typical flight condition of 250,000 feet altitude, 24,000 ft/sec velocity, and a nose diameter of 30 inches. It is seen in the figure that a very small amount of air injection results in a large decrease of heat transfer. For the specific flight conditions used in figure 4, and for the extreme catalytic value of $\rho_w K_w = \infty$, the actual reduction in heat transfer accomplished by the air injection is of the order of 10,000 Btu/lb of air injected.

CONCLUDING REMARKS

A set of closed-form solutions is obtained which enables one to calculate heat-transfer rate to stagnation surfaces with finite catalytic activity and air injection in hypersonic flight provided the boundary layer is chemically frozen.

It is seen that large variations in the surface catalytic activity and therefore the heat transfer can be expected in hypersonic flight. A well programed air injection may considerably reduce the instability in heat transfer due to the variation in catalytic activity.

It is also seen that a very small amount of air is required for sufficiently large reductions in heat transfer so that the air injection scheme may be of practical interest for the flight conditions considered in the present analysis.

The present study is applied only to the cases in which the injected fluid is air and the boundary layer is frozen. It will be worthwhile to investigate the shielding effect of gases other than air in the light of radical diffusions and recombinations, and also, in the presence of the finite chemical reactions within the boundary layer.

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National Aeronautics and Space Administration
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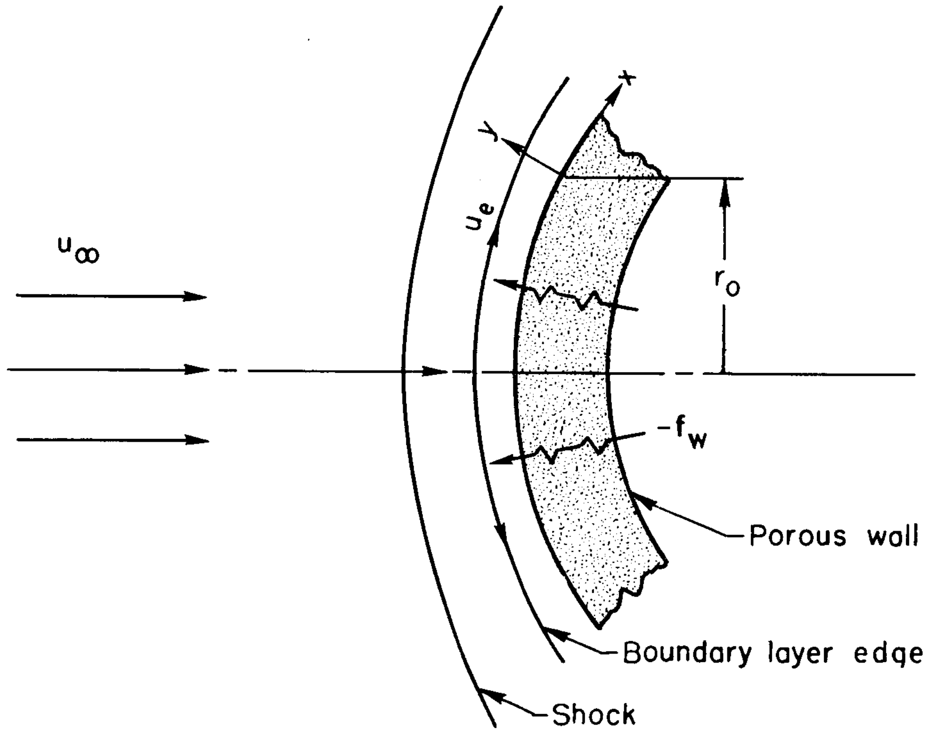


Figure 1.- Physical model.

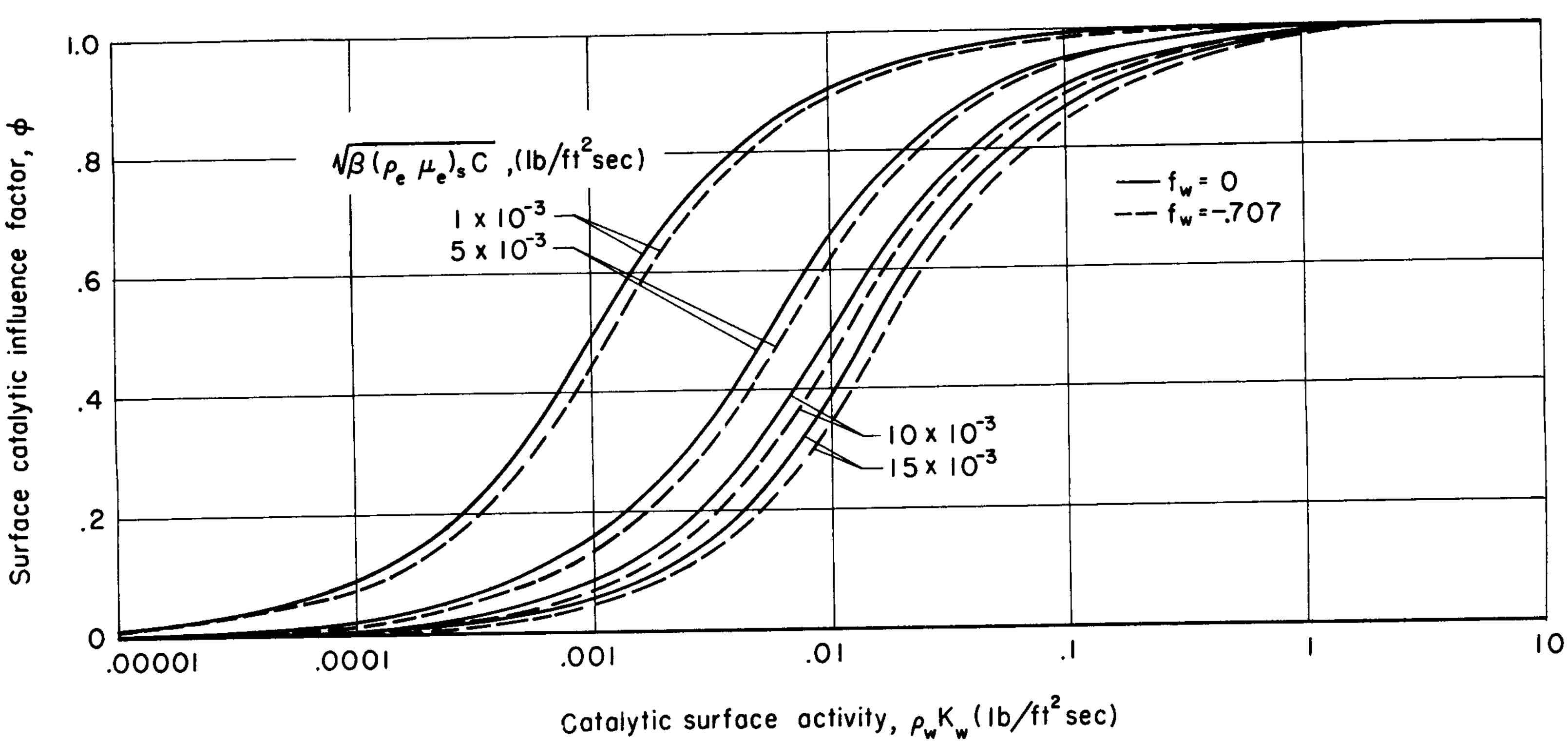
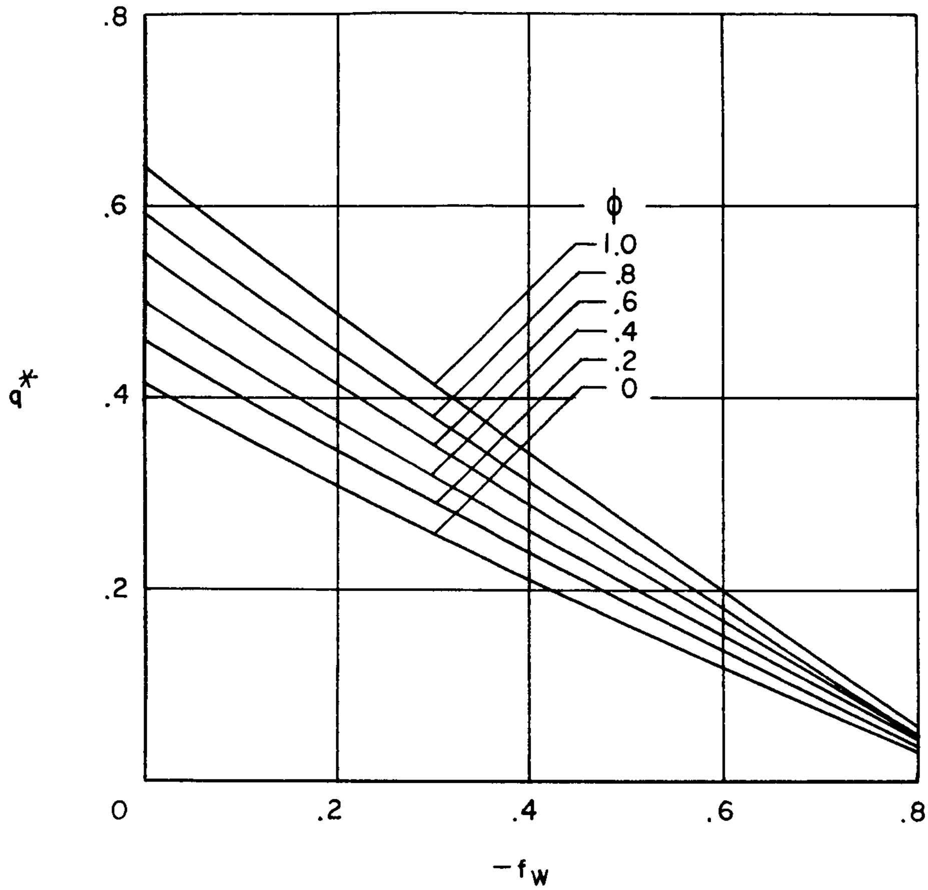
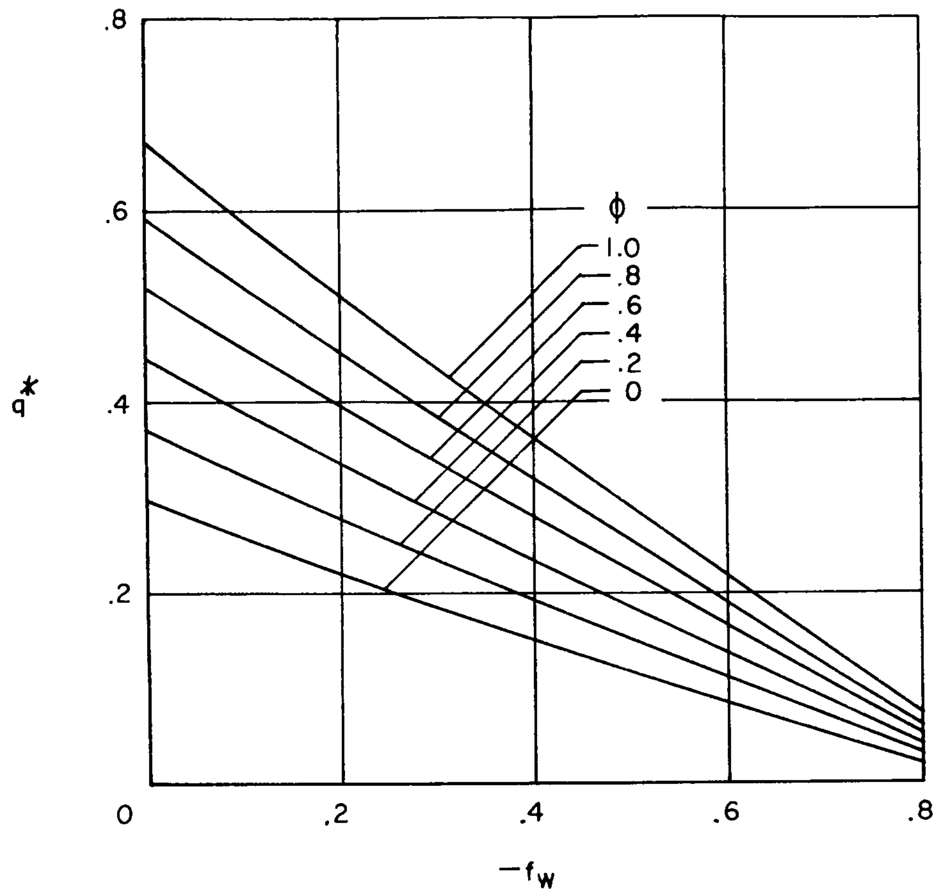


Figure 2.- Variation of surface catalytic influence factor with surface activity.



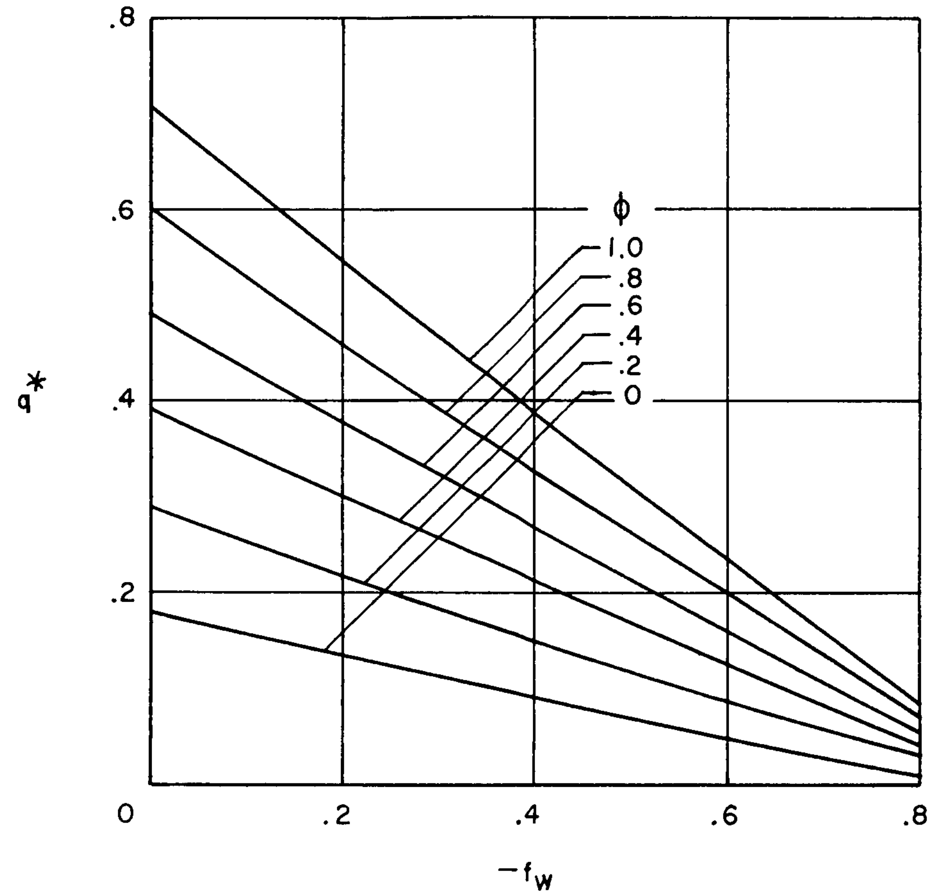
(a) $\Delta h^o m_e / h_{te} = 0.3$

Figure 3.- Variation of heat transfer with fluid injection.



(b) $\Delta h^{o}m_e/h_{te} = 0.5$

Figure 3.- Continued.



(c) $\Delta h^{o}m_{e}/h_{te} = 0.7$

Figure 3.- Concluded.

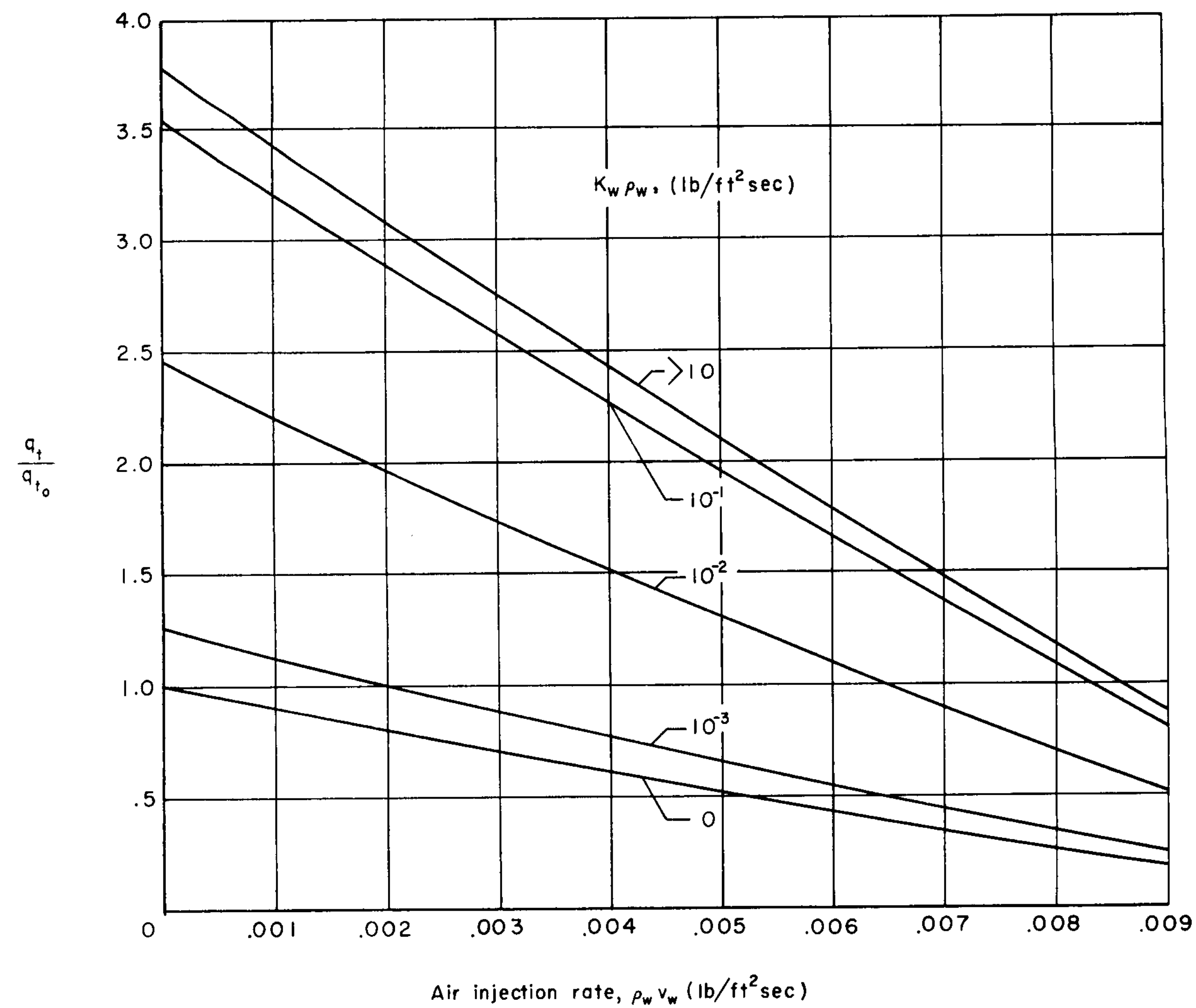


Figure 4.- Variation of heat transfer with air injection; altitude = 250,000 ft, speed = 24,000 ft/sec, nose diameter = 30 in., C = 1.